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Self-healing ring architectures provide high survivability and ensure service availability [1]. Many telecommunication infrastructures in metropolitan and local area networks are implemented with such architectures, and those networks are guaranteed to have 60 ms or less restoration time against link failure [2].

Though optical code-division multiple access (CDMA) is conventionally implemented in broadcast star networks [3]-[5], this technique's unique properties such as large cardinality and soft blocking [6]-[9], provide many advantages when implemented in a ring architecture. First of all, the designed code cardinality is always much larger than the number of subscribers. With large cardinality, a survivable ring network can be built such that there is no need to reserve separate bandwidth or a separate path for link failure. Compared to WDM network that reserves separate wavelengths and TDM network that reserves separate time slots for link failure, optical CDMA ring network is more bandwidth efficient since it can support both links in the ring network to their maximum capacity. Also, full connectivity between nodes is possible without code switching. Secondly, the soft blocking property of optical CDMA allows the addition of subscribers without any hard limit, and new subscribers are easily added to the network without modifying the existing hardware. Thirdly, code-based transmission provides truly asynchronous access capability. The signal is identified with a unique code sequence, so there is no need to distribute a global clock signal in a separate channel for temporal synchronization. Furthermore, full transmission is guaranteed for each node without waiting for the designated transmission time slot. Fourthly, optical CDMA allows heterogeneous data types to coexist in the same link, thus maximizing quality of service in the network. This is especially important for telecommunication networks where services for data, voice and video are integrated, and the quality of service demand for each type differs. Lastly, each code is removed at the destination, which increases the data security by preventing interception of data by downstream nodes.

Previous works have investigated the code-drop unit for optical CDMA ring networks using a terahertz optical asymmetric demultiplexer (TOAD) as the time-gating device [7],[8]. However such an implementation requires a control signal that is synchronized with the clock from the data source. To achieve truly asynchronous operation, a self-clocked code-drop unit has been proposed and demonstrated using a nonlinear optical loop mirror based threshold [9]. The autocorrelation peaks from the desired signal are first extracted from the data stream, which are then wavelength-converted and used as the control signal for the time gating device [10].

In this paper, we first investigate the performance of a complete optical CDMA ring network. The bit-error rate of the desired signal is calculated with Gaussian approximation including multiple-access interference and residual noise from incomplete dropping of signals in the add/drop multiplexers (ADM). This analysis is also carried out for the link failure scenario such that traffic on both links is aggregated temporarily. Furthermore, we experimentally demonstrate a two-node system in asynchronous operation with a protection monitoring circuit and ADM that

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uses only one nonlinear optical loop mirror for signal dropping and restoring.

I. OPTICAL CDMA RING NETWORK DESIGN

A. Network architecture

There are two principle types of ring architecture. One type is unidirectional path-switched ring (UPSR), where two copies of data are sent around the ring in counter directional paths and the receiver selects the best signal from one of the paths. The other type is bidirectional line-switched ring (BLSR), where there is a dedicated path for normal service and another path for backup service [2]. Each type of architecture can be configured with either a two-fiber or a four-fiber link. The two-fiber bidirectional line switching ring architecture can be implemented more efficiently in optical CDMA because of its soft blocking property.

Extensive studies have been presented on code assignment for the fully connected bidirectional ring, where each of the nodes can communicate with every other node [11], [12]. Elrefaie has presented an algorithm that uses the minimum number of wavelengths for a ring with a fixed number of nodes. Similar algorithms can be applied to the optical CDMA ring network by assigning each node with a unique code. The minimum number of codes F needed for fully meshed connectivity with N nodes is shown in (1):

$$F = \left\lceil \frac{N^2 - 1}{4} \right\rceil \quad (1)$$

While the number of wavelengths is limited, the number of codes for optical CDMA can be increased by modifying the number of wavelengths and the number of chips within a bit period.

Due to the soft blocking capability of optical CDMA, traffic can be aggregated with only slight performance degradation. Thus, there is no need to reserve separate bandwidth or a separate backup path for link failure. Both links can carry traffic during normal service. Every node can add and drop signals in both west and east links, as shown in Fig. 1. One way to maximize the quality of service is to put the traffic with high data rates on one link and low data rates on the other link. During a temporary link break down, both west and east links are rerouted and the traffic on both links is aggregated together. Despite the slight degradation in performance, there is no interruption of service during link failure and the bandwidth of the fiber can be utilized the whole time.

B. Add/drop node

The design of the add/drop node is presented in Fig. 2. The proposed add/drop node consists of electronic circuits that monitor link connection, while the all-optical add/drop multiplexers are used to establish transmission between nodes.

The protection-monitoring electronic circuit has two functions: It controls the laser diodes that produce the monitoring signal, and it controls the switches that route the flow of traffic. To avoid interference with the data, the monitoring signal is designed to be a low-power constant continuous-wave light at 1300 nm. This monitoring signal is filtered before the optical CDMA add/drop multiplexers and is directed to the detector in the monitoring circuit. In the case of a link failure between any two nodes on the east link, the following procedure is executed (a similar procedure is executed for a west link failure):

- 1) The monitoring circuit turns on the alarm for east link failure.
- 2) The laser diode for the west link is turned off to notify the following node of the link failure.
- 3) The switch on the west link is connected to the east link and routes the traffic on the two links together.

To perform optical add/drop in the ring, the monitoring signal and the data are separated when the traffic comes in to the node. The data is directed to the all-optical add/drop multiplexers (ADM). The principles of each ADM are illustrated in Fig. 3. When the data on the links enters the ADM, the decoder reconstructs the signal so that the designated signal has autocorrelation peaks while the other signals have crosscorrelation peaks. The main device that distinguishes the desired data from the undesired data is the nonlinear-optical loop mirror (NOLM). It separates the autocorrelation peaks of the desired data from the cross-correlation peaks of the undesired data by distinguishing the pulse intensity [13]. The NOLM consists of a dispersion shifted fiber, an optical attenuator, and a polarization controller. Since the autocorrelation peaks from the desired data have higher intensities than the crosscorrelation peaks from the undesired data, the desired data is directed to the transmitting port of the NOLM, and the undesired data is directed to the reflection port. The drop data from the transmitting port is sent to the receiver. The thru data from the reflection port passes through another encoder so that the data is restored to the same state as before the ADM. After the encoder, the thru data is coupled with the newly added data to be sent onto the links.

II. PERFORMANCE ANALYSIS FOR OPTICAL CDMA RING NETWORKS

A. Probability of error in the ideal optical CDMA ring network

Incoherent optical CDMA networks implementing amplitude modulation with optical orthogonal codes support complete asynchronous access and accommodate various data types. One type of optical orthogonal codes is carrier-hopping prime codes (CHPC), which can be described by $(L \times N, \omega, \lambda_a, \lambda_c)$ [14], where $L \times N$ is the size of the matrix, ω is the weight of the code (the number of wavelength for CHPC), λ_a is the maximum autocorrelation sidelobe, and λ_c the

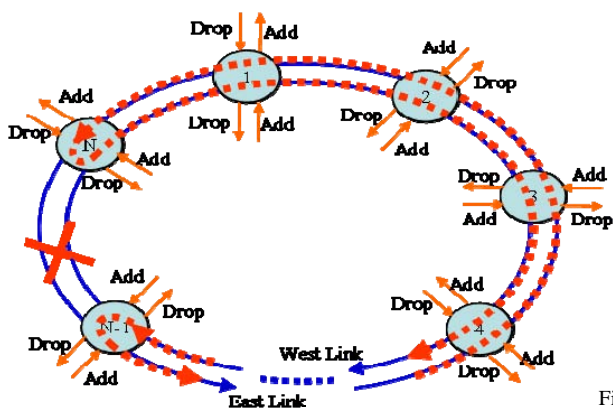


Fig. 1. Two-fiber bidirectional optical CDMA ring network.

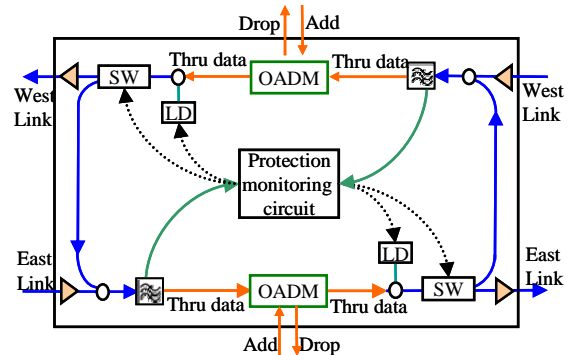


Fig. 2. Design of the optical CDMA add/drop nodes with protection monitoring circuit and optical add/drop multiplexers on both links. SW: switch; LD: laser diode; OADM: optical add/drop multiplexer.

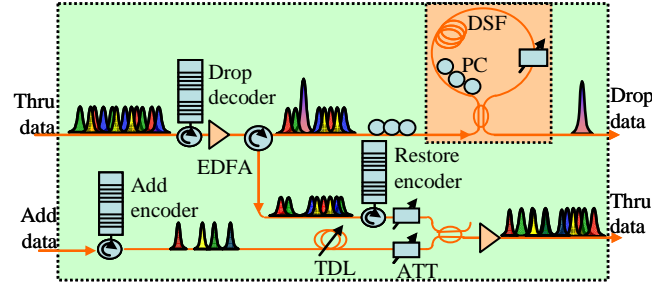


Fig. 3. Schematic of the optical CDMA add/drop multiplexer. EDFA: erbium-doped fiber amplifier; TDL: tunable optical delay line; ATT: attenuator; PC: polarization controller; DSF: dispersion shifted fiber.

maximum cross-correlation value. We evaluate the performance of such networks by calculating the probability of error for the ideal system, using the assumptions that the only source of noise is from multiple-access interference and each pulse has the same power. The hit probability q_i of the desired signal and i -th type of interfering signal is calculated in (2) [14]

$$q_i = \frac{\omega_a \omega_i}{2 \max(\omega_a, \omega_i) N_i} \quad (2)$$

where ω_a is the weight of the desired signal, and ω_i is the weight of the interfering signal. The average power for a received 0-bit and 1-bit, and the noise variance from MAI are presented in (3), (4), and (5).

$$\bar{P}_0 = \sum_{\forall i} k_i q_i \quad (3)$$

$$\bar{P}_1 = \omega_a + \sum_{\forall i} k_i q_i \quad (4)$$

$$\sigma_0^2 = \sigma_1^2 = \sum_{\forall i} k_i q_i (1 - q_i) \quad (5)$$

Here, k_i is the number of interfering users with the i -th data type. The error probability of the system is approximated by (6) [14].

$$P_{eG} = Q\left(\frac{1}{2}\sqrt{SNR}\right) = Q\left(\frac{1}{2} \frac{\omega_a}{\sqrt{\sum_{\forall i} k_i q_i (1 - q_i)}}\right) \quad (6)$$

$$\text{where } Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{y^2}{2}} dy$$

B. Probability of error in the non-ideal optical CDMA ring network

We apply the same probability-of-error analysis on the non-ideal two-fiber bidirectional optical CDMA ring network, but in addition to multiple-access interference, we also include the dropped residual signal from time gating/thresholding devices in the add/drop multiplexers. Before considering the probability of error, first we have to investigate how the signals interfere with each other in two-fiber bidirectional ring networks. The interference depends on the connection configuration. The best scenario would be one in which every node is transmitting to the adjacent node, so that all the codes are removed without interfering with each other. The worst case

scenario would be one in which every node is transmitting to the furthest node on the link, resulting in $N-2$ interfering users on every link segment.

When incomplete dropping of desired signals and accidental dropping of partial undesired signals occurs, additional noise is added to the link, and we can approximate the residual signals after the add/drop multiplexers (ADM) with a Gaussian distribution. The average power of the received 0-bit and 1-bit are modified in (7) and (8)

$$\bar{P}_0 = \sum_{\forall i} q_{i,j} r_c^j \quad (7)$$

$$\bar{P}_1 = \omega_a(1-r_a)r_c^j + \sum_{\forall i} q_{i,j} r_c^j \quad (8)$$

where r_c^j is the residual of the crosscorrelation peaks from i -th data type after j -th ADMs and r_a is the residual of the autocorrelation peak after the ADM of the destined receiver. The variance of multiple access interference is calculated in (9)

$$\sigma_{MAI}^2 = \sum_{\forall i} q_{i,j}(1-q_{i,j})r_c^j \quad (9)$$

The new error probability is presented in (10)

$$P_{e|G} = Q\left(\frac{\omega_a(1-r_a)r_c^j}{2\sqrt{\sigma_{MAI}^2}}\right) \quad (10)$$

Fig. 4 compares the performance of the ideal ring network calculated using (6) and the performance of the non-ideal ring network calculated using (10) with residuals where $r_c=99\%$ and $r_a=5\%$. The (12x97, 12, 0, 1) CHPC parameters used in the calculation describe a 10-Gbit/s system with a 1-ps full-width half-maximum pulse width. The performance of the ring network is degraded accordingly to the increase in number of simultaneous transmissions on a link segment. The calculation is done with the maximum number of interfering users where every node is transmitting to the furthest node, i.e. the worst scenario.

As mentioned previously, the heterogeneous data characteristic of an optical CDMA ring network allows the two traffic links that carry heterogeneous data types to be aggregated together during link failure without complicated network management. The error probabilities of the aggregated links for the ideal ring network calculated using (6) are shown in Fig. 5. The analysis assumes that one link carries high data rate traffic by implementing (12x97, 12, 0, 1) CHPC, and the other link carries low data rate traffic by implementing (10x199, 10, 0, 1) CHPC. The normal operation is shown with hollow data points, and the link failure operation is shown with cross and star data points. If both links are supporting the maximum number of nodes, with $BER=10^{-12}$, during link failure, the performance for the high data rate link would be

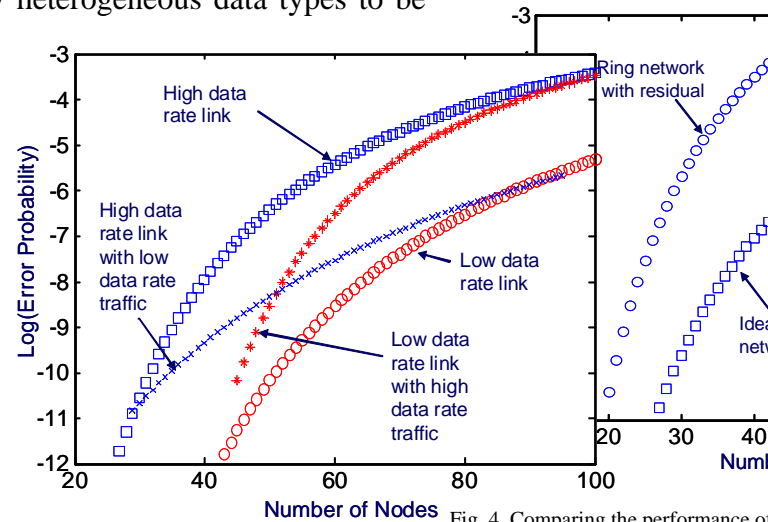


Fig. 5. Performance of the ideal ring network carrying different types of data in the ring. Fig. 4. Comparing the performance of ideal add/drop and ring network with each link (hollow data points), and the effect during link failure when traffic on both links are aggregated together (cross and star data points).

degraded to $\text{BER}=10^{-7}$, and the low data rate link would be degraded to $\text{BER}=10^{-5}$.

III. EXPERIMENTAL DEMONSTRATION

A. Experimental network testbed

An experimental setup of a two-node optical CDMA ring network is shown in Fig. 6. The schematic shows the worst case connection, where each node receives its own data, i.e. the data goes through all the nodes and undergoes both the decoding and restoring stages at the other node. The detailed explanation of the functionality of the monitoring and protection circuits, and the operation of the add/drop multiplexers (ADMs) have been discussed in the design section. For the experimental demonstration, only one link is carrying data during normal operation, thus one ADM is incorporated on the east link of the node. The two nodes are sharing the same optical source but they are encoded differently. The received signal at one of the nodes is monitored, as the two nodes operate similarly.

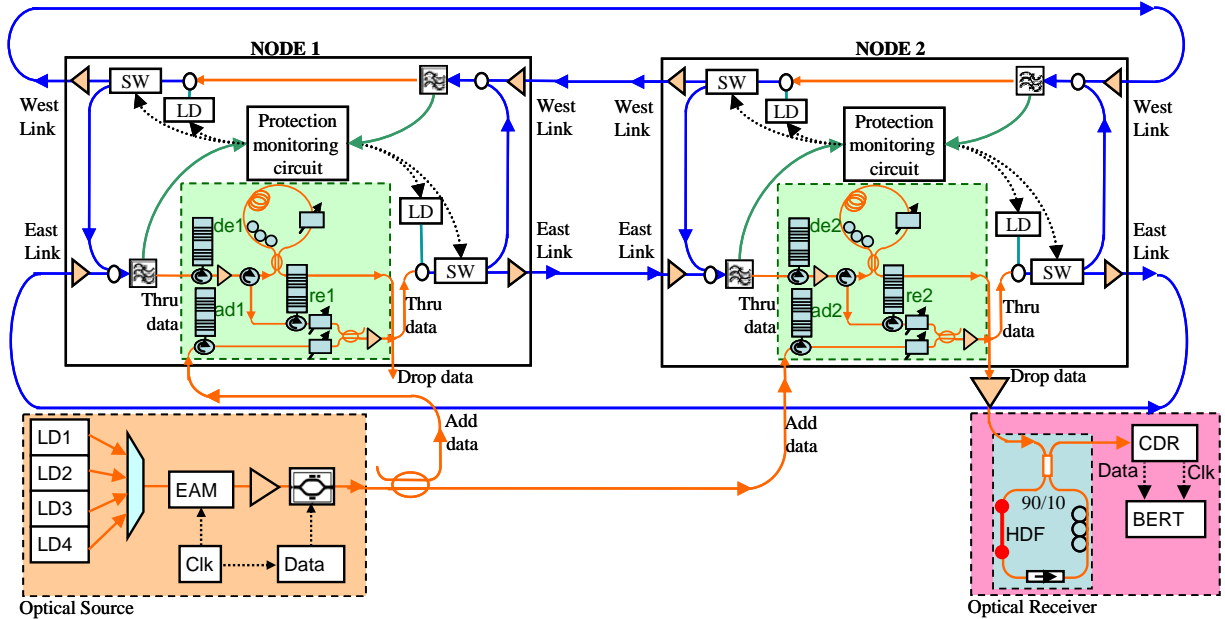


Fig. 6. Experimental setup of two-node ring network. LD: laser diode; EAM: electro-absorption modulator; Clk: clock; HDF: highly GeO₂-doped fiber; CDR: clock and data recovery unit; BERT: bit-error rate tester.

The optical source consists of four CW laser diodes that generate wavelengths centered at 1552.92 nm, 1551.72 nm, 1550.92 nm, and 1550.12 nm. A short pulse train that has 10 ps full-width half-maximum pulse width is obtained using the electro-absorption modulator as a pulse carver with a 2.5 GHz clock source. The pulse train is then modulated by a $2^{31}-1$ pseudorandom bit sequence at 2.5 Gbit/s using a LiNbO₃ Mach-Zehnder modulator. The optical signal is split and sent to the optical CDMA ADM's add encoders.

The implemented ADM uses a nonlinear-optical loop mirror (NOLM) as the code-drop device. The dispersion-shifted fiber is 2 km in one NOLM, and 2.4 km in the other one. The codes implemented during the experiment are (4x17, 4, 0, 1) CHPC, with four wavelengths and seventeen time chips. The code sequence for node 1's add encoder is (0, 3, 6, 9), where the numbers indicate the chip slots for the four wavelengths from the optical source respectively. The

drop decoder and the restore encoder are matched with the add encoder. The code for node 2's add encoder is (0, 7, 14, 4).

The receiver has another NOLM-based thresholder [9] for suppressing the amplitude noise in the autocorrelation peaks. The thresholded signal is sent to an off-the-shelf clock data recovery unit (HP 83446A OC-48/STM 16). The optical signal and the clock signal are recovered asynchronously for bit-error-rate measurements.

B. Experimental results and discussion

The dropping and passing capability of the nonlinear-optical loop mirror is first investigated separately without connecting to the ring configuration. The reflection port with the crosscorrelation peaks and residual autocorrelation peaks are shown in Fig. 7(a). After passing the thru signal from the reflection port to a matched encoder, it is restored to its original sequence, shown in Fig 7(b), and can be directed to the next node. The dropped signal with clean autocorrelation peaks are the desired signal, shown in Fig. 7(c).

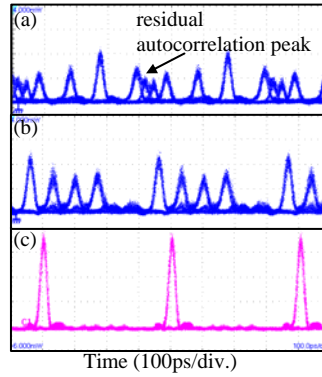


Fig. 7. Waveforms after nonlinear optical loop mirror dropping module. (a) Reflection port of the NOLM with undesired thru signal before restoration (crosscorrelation peaks). (b) Restored thru signal. (c) Dropped desired signal (autocorrelation peaks).

Two connection configurations have been tested. The first one simulates the best scenario, where the signal is added at one node, and it is immediately dropped at the adjacent node. Fig. 8 (a) and (c) show the two newly added signals and the residual autocorrelation peaks. The residual autocorrelation peaks from the NOLM are very small and have little effect on the thru signal. Fig. 8 (b) and (d) show the dropped autocorrelation peaks for the two nodes. Both signals have very good eye openings and little amplitude noise.

The second connection configuration tests the performance of the worst case scenario, where the signal is received after passing through all the other nodes. In this configuration, both the multiple-access interference and the residual noise from the time gating devices affect the system performance. After NOLM, noise is added onto the signal at the reflection port. The signals on the link between the two nodes are shown in Fig. 9(a) and (b). The signals are a combination of the newly added signal and the restored signal after the NOLM. Fig. 9 (c) and (d) show the dropped signal at node 1 and node 2.

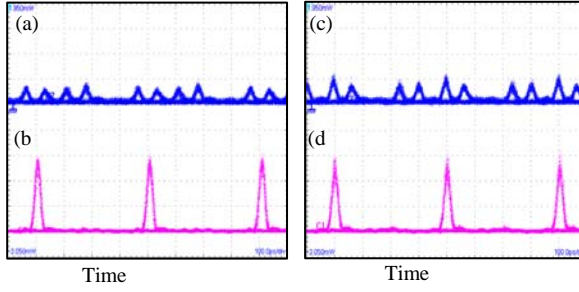


Fig. 8. Waveforms for direct dropping. (a) Signal on the thru link after node 1. (b) Dropped signal at node 1. (c) Signal on the thru link after node 2. (d) Dropped signal at node 2.

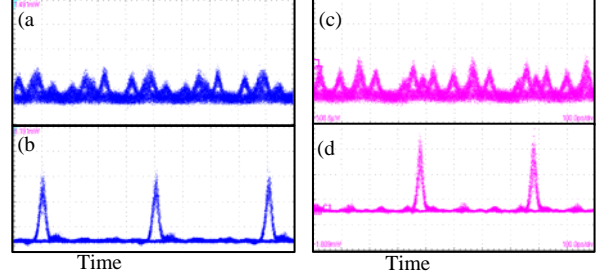


Fig. 9. Waveforms for indirect dropping, after signal passing through one node. (a) Signal on the thru link after node 1. (b) Dropped signal at node 1. (c) Signal on the thru link after node 2. (d) Dropped signal at node 2.

The performance of the complete network is characterized by measuring bit-error rate (BER) as a function of the average received power at the CDR's photodetector, shown in Fig. 10. To demonstrate the use of the protection monitoring circuits, we compare the BER measurements for the system without the protection monitoring circuit to the BER measurements with the circuit. For system with protection monitoring circuit, we investigate the normal operation where the signal goes through the east link as shown in fig. 1 and the link failure operation where the signal is rerouted to the west link when the east link path is broken. There is 6 dB loss for the signal after traveling in the west link since it goes through additional couplers and switches. The BER curves for the best connection scenario, direct dropping, are indicated by triangular data points. Error-free transmission is obtained with 3.5 dB power penalty without additional signal processing at the receiver. The BER curves for the worst connection scenario, indirect dropping, are indicated by circular data points. Because of the residual noise from the add/drop multiplexers, a NOLM for amplitude noise suppression is added at the receiver. The BER curve for the indirect dropping with signal going through the west link has different slope from the other two paths. This is because of the additional power needed to compensate for the loss in the protection circuits also contributes

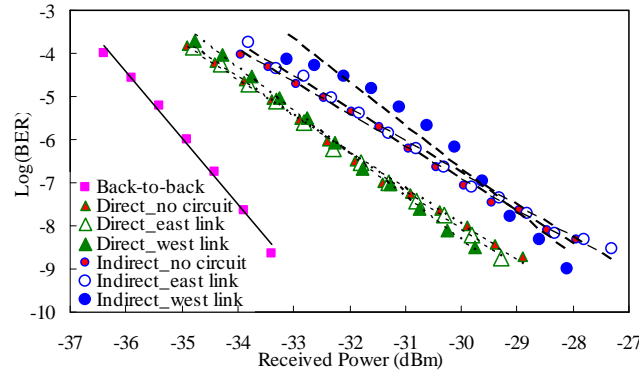


Fig. 10. Bit-error rate measurements for three types of configurations: back-to-back; direct dropping where signal is drop immediately at the next node in the ring network (triangular data points), and indirect dropping where signal is dropped after passing through one node (circular data points). No circuit: signal doesn't go through protection circuit; east link: normal operation where signal goes through working link; west link: link failure operation where signal goes through backup link.

more noise to both 0-bit and 1-bit signals. For the signal that goes through west link during link

failure, error free transmission is obtained with 5.3 dB power penalty.

IV. CONCLUSION

An optical CDMA ring network with protection monitoring circuits and all-optical add/drop multiplexers for optical CDMA signals has been proposed and analyzed. A complete two-node optical CDMA ring network with error-free transmission has been experimentally demonstrated for a truly asynchronous operation, and the performance has been characterized. In optical CDMA ring networks, other than multiple-access interference, crosscorrelation peaks distortion and residual autocorrelation peaks from the code dropping device also contribute to the performance degradation. However, with additional signal processing at the receiver using a threshold based in nonlinear optical loop mirror, $\text{BER}=10^{-9}$ is achieved. The experimental demonstration shows that the proposed network is a viable and bandwidth efficient design that utilizes the unique characteristics of optical CDMA.

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